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GREEN CHEMISTRY AND ENGINEERING OPPORTUNITY ASSESSMENT (GC&EOA)
To
US Army

Final Report
A Case Study in Sustainable Remediation

November 30, 2009

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Prepared by
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This report was prepared under contract for the Army Environmental Policy Institute (AEPI) by the National Defense Center for Energy and Environment (NDCEE), operated by Concurrent Technologies Corporation (*CTC*). It discusses specific efforts conducted under Contract Number W74V8H-04-D-0005, Task Number 0469, "Green Chemistry and Engineering Opportunity Assessment (GC&EOA) for U.S. Army". This report presents the sustainability frameworks of Green Chemistry and Green Engineering and uses them as a basis to identify opportunities for environmental improvement and innovation within the U.S. Army. As a specific case study, this report evaluates the Army's activities around the remediation of emerging contaminants and presents a set of sustainability metrics to assist the Army in evaluating the environmental preference of various treatment technologies. These metrics are then applied to a specific treatment technology, namely groundwater extraction and above-ground treatment of Perchlorate.

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REPORT SUMMARY

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STRATEGIC COMMUNICATIONS

The NDCEE team recommends initial briefing of this report to the Director, AEPI followed by briefings to the Deputy Assistant Secretary of the Army (DASA) for Environment Safety and Occupational Health (ESOH) and the Special Assistant(s) responsible for clean-up and remediation within the Office of the DASA.

During the development of this project focus and determination of area of need for the Army, the project team worked with a group of stakeholders from the United States Army Construction Engineering Research Laboratory, Pollution Prevention Division. The NDCEE team recommends AEPI coordinate a briefing and discussion with the stakeholder team to generate further discussion about the potential applicability of this assessment methodology as a decision support tool in the field. It is recommended that the stakeholder team discuss other tools and methodologies and gain an understanding of the requirements and objectives of further efforts in using these assessments to inform policy decisions and technology implementation decisions.

Appendix A

AEPI Report – November 2009

Green Chemistry and Engineering Opportunity Assessment for the U.S. Army:

A case study in sustainable remediation

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AEPI Report

Green Chemistry and Engineering Opportunity Assessment for the U.S. Army:
A case study in sustainable remediation

November 2009

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The images on the cover shows an Army Corps of Engineering remediation project of Rattlesnake Creek in Tonawanda, New York, which took place from 2005-2006.

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Preface

This report was prepared under contract for the Army Environmental Policy Institute (AEPI) by the National Defense Center for Energy and Environment (NDCEE), operated by Concurrent Technologies Corporation (*CTC*). It discusses specific efforts conducted under Contract Number W74V8H-04-D-0005, Task Number 0469, “Green Chemistry and Engineering Opportunity Assessment (GC&EOA) for U.S. Army”. This report presents the sustainability frameworks of Green Chemistry and Green Engineering and uses them as a basis to identify opportunities for environmental improvement and innovation within the U.S. Army. As a specific case study, this report evaluates the Army’s activities around the remediation of emerging contaminants and presents a set of sustainability metrics to assist the Army in evaluating the environmental preference of various treatment technologies. These metrics are then applied to a specific treatment technology, namely groundwater extraction and above-ground treatment of perchlorate.

The views expressed do not necessarily reflect the official policy or position of the Department of Defense (DoD), Department of the Army, or the U.S. Government.

The mission of AEPI is to assist the Army Secretariat in developing forward-looking policies and strategies to address environmental issues that may have significant future impacts on the Army. In the execution of this mission, AEPI is further tasked with identifying and assessing the potential impacts on the Army of emerging environmental issues and trends.

Please direct comments pertaining to this report to:
Director, Army Environmental Policy Institute
1550 Crystal Drive, Suite 1301
Arlington, Virginia 22202-4144

List of Acronyms

µg/L	micrograms per liter
AEPI	Army Environmental Policy Institute
AFCEE	Air Force Center for Engineering and Environment
BMP	Best Management Practice
CERL	Construction Engineering Research Laboratory
CMRMD	Chemical Material and Risk Management Directorate
CTC	Concurrent Technologies Corporation
DoD	Department of Defense
EC	Emerging Contaminant
EPA	Environmental Protection Agency
GAC	Granular Activated Carbon
GC&EOA	Green Chemistry and Engineering Opportunity Assessment
GHG	Greenhouse Gases
gpm	gallons per minute
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
MMR	Massachusetts Military Reservation
MW	megawatt
NDCEE	National Defense Center for Energy and Environment
CO_2	Carbon Dioxide
OSD	Office of the Secretary of Defense
OSWER	Office of Solid Waste and Emergency Reponses (of the USEPA)
OUSD	Office of the Under Secretary of Defense
RDX	Royal Demolition Explosive
S&T	Science and Technology
SRT	Sustainable Remediation Tool
SURF	Sustainable Remediation Forum
TARDEC	Tank Automotive Research and Development Engineering Center
TCE	Trichloroethylene
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency

Executive Summary

Building on the Army's success with reducing toxics use and release through pollution prevention measures, the Army Environmental Policy Institute (AEPI) is looking for innovative "green" chemical and/or engineering approaches to identify those processes which can be changed or eliminated to make these processes more environmentally friendly using the latest knowledge available. Green Chemistry and Green Engineering are frameworks for effective and sustainable design of new products, processes, and systems. Using principles developed under these frameworks, the present project conducted a broad opportunity assessment for the U.S. Army. As a specific case study, Green Chemistry and Green Engineering were used to develop a set of sustainability metrics and an associated evaluation tool for choosing appropriate remediation technologies, in particular for emerging contaminants, as defined by the Office of the Secretary of Defense (OSD), Chemical Material and Risk Management Directorate (CMRMD).

Sustainable remediation is currently a major topic within the remediation community, including groups such as the United States Environmental Protection Agency (USEPA), the Sustainable Remediation Forum, academic researchers, and the military. Section 2 provides a context for the discussion of sustainable remediation by reviewing past efforts and findings, particularly around the effectiveness and accuracy of various metrics. Many groups have proposed sets of metrics that cover both the primary effects of remediation (those related to residual contamination, such as potential remaining health risks), and secondary impacts that stem from the installation and operation of the treatment technology itself. These include energy use, air emissions from electricity generation needed for pumping systems, increases in local traffic, and many other environmental and social issues. Section 3 reviews many of the proposed metrics against the 24 Principles of Green Chemistry and Green Engineering, analyzing which principles are well-followed and where there are potential gaps. Based on these gaps and in consultation with industry experts, additional sustainability metrics are proposed in Section 4, covering the main topics of:

1) Treatment Efficiency
2) Residuals
3) Inherently Benign
4) Worker Health and Safety
5) Social/Cultural Factors
6) Water, Energy, and Emissions
7) Ecosystem Considerations

Using the proposed metrics in these seven categories, an open, Excel-based spreadsheet tool was developed to facilitate technology evaluation and choice. The tool uses a hierarchical weighting system and transparent scoring for maximum flexibility, so that future users can specify for themselves, for example, what constitutes a high level of water use, how much relative weighting should be applied to different metrics of treatment efficiency, or the proper weighting of ecosystem considerations versus worker health and safety. The tool has been developed to enable the Army to systematically compare different technologies side-by-side for a single site, though different sites can also be assessed. For every type of evaluation, the tool automatically creates summary sheets that show in clear, visual terms the performance of the different treatment technology choices on each metric and each aggregate category.

In order to demonstrate and validate the tool, an initial assessment was performed of the pump-and-treat system for perchlorate that was installed at the Massachusetts Military Reservation in Cape Cod, Massachusetts. Several technical documents and online sources were used to gather empirical data about the treatment, such as water and energy use, the level of community involvement, and hazardous waste generated as a result of treatment. A technology summary sheet was produced by the tool, and is described in detail in Section 5 of this report. The analysis that the technology performed poorly overall in the evaluation, mainly due to high energy and water use, the lack of material reuse and recycling possibilities, and a long treatment time.

1 Introduction

For the past several years the Army has had an ongoing effort to reduce the toxicity of its processes through the use of pollution prevention techniques. These techniques include reduction and/or substitution of toxic solvents, metals and other chemicals with non-toxic alternatives. These practices have significantly reduced the volume and toxicity of the Army wastes, but have been somewhat limited in that changes were often done on an individual basis or without a full understanding of the chemical/physical interactions of the hazardous materials, coatings, solvents or other intermediates being used. The Army Environmental Policy Institute (AEPI) is looking for innovative "green" chemical and/or engineering approaches to identify those processes which can be changed or eliminated to make these processes more environmentally friendly using the latest knowledge available.

One approach being adopted by many commercial companies to evaluate and reduce their hazardous chemicals and processes has been to adopt the "Twelve Principles of Green Chemistry" (Box 1) and the "Twelve principles of Green Engineering" (Box 2).

Green Chemistry

Green Chemistry is defined as the "design of chemical products and processes to reduce or eliminate the use and generation of hazardous substances" through the utilization of a set of twelve principles. This definition and the concept of green chemistry were first formulated at the beginning of the 1990s some 20 years ago. In the years following, there has been international adoption that resulted in the creation of literally hundreds of programs and governmental initiatives on Green Chemistry around the world with initial leading programs located in the U.S., United Kingdom, and Italy. These have played a significant role in informing sustainable design. Important early programs were the US Presidential Green Chemistry Challenge Awards established in 1995, the Green Chemistry Institute founded in 1997 and the publication of the first volume of the now well-established Green Chemistry journal of the Royal Society of Chemistry.

The Green Chemistry approach strives to achieve sustainability at the molecular level. Because of this goal, it is not surprising to see it being applied to all sectors of the industry. From aerospace, automobile, cosmetic, household products, pharmaceutical or agriculture, there are hundreds of examples of successful applications. U.S. Presidential Green Chemistry Challenge Awards have featured recipients that have ranged from traditional chemical manufacturing to electronics, pest control, and energy generation.

The concept of Green Chemistry had a large impact due to the fact that it went beyond the research laboratory in isolation and touched industry, education, environment, and the general public. The field of Green Chemistry has demonstrated how chemists can design next generation products and processes so that they are profitable while being good for human health and the environment.
The three main points about the Green Chemistry Framework can be summarized as:

1. Green Chemistry designs across all stages of the chemical life cycle.
2. Green Chemistry seeks to design the inherent nature of the chemical products and processes to reduce their intrinsic hazard.
3. Green Chemistry works as a cohesive system of Principles or design criteria.

The Twelve Principles of Green Chemistry are design criteria or guidelines that provide the framework for sustainable design. They constitute an overarching construct for the design of safer chemicals and chemical transformations. These Principles can be used by the Army to evaluate chemicals and products that it uses directly for military purposes (such as ammunition) and for support purposes (such as cleaning and purification), or to guide the development of new military technology (such as nanomaterial-enhanced gear).

This is the aim of Green Chemistry, to reduce hazards across all the life cycle stages. Hazard is defined as the ability to cause adverse consequence to humans or the environment. Intrinsic hazard of a

chemical substance or a chemical process can be minimized through design. This applied to hazard at every level of a process, whether it is toxicity, physical hazards (*e.g.,* explosion, flammability) or global hazards such as stratospheric ozone depletion. Risks based on these hazards may rise from the nature of the feedstock and raw materials that are used to the chemical transformations as well as the final products that are made. Only a careful design will reduce or eliminate intrinsic hazards within chemicals and processes; a design based on the integration of the twelve principles as one cohesive set. Green Chemistry is not only about achieving enhanced efficiency nor is it only about pollution/waste prevention; it is about the goals sustainability.

Box 1: The Principles of Green Chemistry

PRINCIPLE 1 - Prevention. It is better to prevent waste than to treat or clean up waste after it is formed.

PRINCIPLE 2 - Atom economy. Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.

PRINCIPLE 3 - Less Hazardous Chemical Synthesis. Whenever practicable, synthetic methodologies should be designed to use and generate substances that posses little or no toxicity to human health and the environment.

PRINCIPLE 4 - Designing Safer Chemicals. Chemical products should be designed to preserve efficacy of the function while reducing toxicity.

PRINCIPLE 5 - Safer Solvents and Auxiliaries. The use of auxiliary substances (solvents, separation agents, etc.) should be made unnecessary whenever possible and, when used, innocuous.

PRINCIPLE 6 - Design for Energy Efficiency. Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.

PRINCIPLE 7 - Use of Renewable Feedstocks. A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.

PRINCIPLE 8 - Reduce Derivatives. Unnecessary derivatization (use of blocking groups, protection/ deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.

PRINCIPLE 9 - Catalysis. Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.

PRINCIPLE 10 - Design for Degradation. Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.

PRINCIPLE 11 - Real-time analysis for Pollution Prevention. Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.

PRINCIPLE 12 - Inherently Safer Chemistry for Accident Prevention. Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

Source: Anastas and Warner (2000)

Green Engineering

Green Engineering is the design, discovery and implementation of engineering solutions for sustainability. The approach is scalable applying across molecular, product, process and system. This approach is as broad as the disciplines of engineering themselves and includes molecular and bio-engineering, civil, electrical, mechanical, environmental and systems engineering.

The Principles of Green Engineering provide a framework for understanding and represent a reflection of those engineering techniques that are being used to become more sustainable. While there are significant, creative and important examples of engineering solutions that are being developed, they are neither comprehensive nor systematic. The Twelve Principles should be thought of not as rules, laws or inviolable standards. They are instead a set of guidelines for thinking in terms of sustainable design criteria that, if followed, can lead to useful advances for a wide range of engineering problems.

Box 2: The Principles of Green Engineering

PRINCIPLE 1 - Designers need to strive to ensure that all material and energy inputs and outputs are as inherently non-hazardous as possible.
PRINCIPLE 2 - It is better to prevent waste than to treat or clean up waste after it is formed.
PRINCIPLE 3 - Separation and purification operations should be a component of the design framework.
PRINCIPLE 4 - System components should be designed to maximize mass, energy and temporal efficiency.
PRINCIPLE 5 - System components should be output pulled rather than input pushed through the use of energy and materials.
PRINCIPLE 6 - Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse or beneficial disposition.
PRINCIPLE 7 - Targeted durability, not immortality, should be a design goal.
PRINCIPLE 8 - Design for unnecessary capacity or capability should be considered a design flaw. This includes engineering “one size fits all” solutions.
PRINCIPLE 9 - Multi-component products should strive for material unification to promote disassembly and value retention. (minimize material diversity)
PRINCIPLE 10 - Design of processes and systems must include integration of interconnectivity with available energy and materials flows.
PRINCIPLE 11 - Performance metrics include designing for performance in commercial “after-life”.
PRINCIPLE 12 - Design should be based on renewable and readily available inputs throughout the life cycle.

Source: Anastas and Zimmerman (2004)

The Principles will be a set of parameters in a complex system where there will be synergies in which progress toward achieving the goal of one principle will augment progress toward several other principles. In other cases, there may be trade-offs between the application of two principles. Those trade-offs can only be resolved by the specific choices and values of the practitioners within the context of their specific situation or within their society. In the end, all sustainability is local and the framework of the Twelve Principles of Green Engineering is a tool to aid in consciously and transparently addressing those design choices relevant to fundamental sustainability.

In order to address the issues of sustainability, Green Engineering needs to approach the fundamentals of design in a manner that takes into account:

- Life Cycle considerations
- Multi-scale applications; *e.g.*, products, processes and systems

In addition, the design of engineering solutions must keep in mind the broader array of scales that can be addressed. If applied to a narrowly defined target, the Twelve Principles of Green Engineering could have assisted in making a more sustainable vacuum tube for electronics without the broader perspective that allowed for the development of the transistor. As leapfrog technologies become increasingly important in addressing fundamental sustainability challenges such as energy, food, water, resource depletion, the broad perspective of multi-scale application of the Twelve Principles is essential for long-term success of technology transition in the DoD and the Army.

The purpose of the current report is to use these 24 Principles as a framework for identifying and discussing several opportunities within the U.S. Army generally, and for sustainable remediation programs for emerging contaminants specifically.

1.1 Initial Opportunity Assessment

The scope of the study was initially and intentionally quite broad to allow for maximum flexibility in securing a high impact and high value project focus. There are numerous opportunities within the Army to focus Green Chemistry and Green Engineering efforts and after identifying several leads, the decision was ultimately made to focus specifically on sustainable remediation.

Early contact was made with the Fuel Technology and Lubricants group of the U.S. Army Tank Automotive Research and Development Engineering Center (TARDEC). This group is responsible for a wide range of products including: Engine Oils, Gear Lubricants, Preservative General Purpose lubes, Preservative Engine Oils, Greases, Hydraulic Fluids (several specs including biobased hydraulic fluid), Brake Fluids, Solid Film Lubricants - heat and air cure, Coolants, Fuels, Solvents - MIL-PRF_680, and Stabilizer/Biocide additive system. Clearly these types of products would provide a rich and deep portfolio for opportunities leading to quality case studies about the environmental and economic benefits of such pursuits. However, this area proved to be broad and require research that would have been beyond the resources of this task.

Several efforts were made to find an appropriate project within the research lab organizations. While this is the most powerful place to pursue Green Chemistry and Green Engineering by ensuring that these approaches are inherently part of any new product, process or system design being developed and implemented, it was difficult to find a specific topic to pursue. There were barriers to pursuing opportunities in the research space related to confidential or secure information, previously established performance specifications that did not include environmental considerations, or a notion that green chemistry and green engineering was already being pursued. Overcoming these barriers would lead to a powerful opportunity to demonstrate the potential of green chemistry and green engineering for the army.

1.2 Moving Towards Sustainable Remediation

After a review of Green Chemistry and Green Engineering opportunities within the Army, the project focused on applying the 24 Principles to a particular environmental technology issue that the Army faces, namely choosing appropriate remediation technologies for soil and groundwater contamination clean-up. Making technology choices for emerging contaminants – those that do not have an established remediation track record because they are not regulated or are not commonly metered – is a particular challenge. The application of Green Chemistry and Green Engineering principles to remediation falls into the topic of sustainable remediation, which has received significant attention in recent years. Past research and efforts by both civilian and military groups are reviewed in Section 2.

The choice of sustainable remediation technology evaluation as a case study for Green Chemistry and Green Engineering will support the Army as it responds to the August 10, 2009 memorandum ‘Consideration of Green and Sustainable Remediation Practices in the Defense Environmental Restoration Program’ from the Office of the Under Secretary of Defense (OUSD). The memo requests information on current efforts to incorporate sustainability in Defense remediation practices, including technology evaluation and selection.

Remediation technology evaluation has traditionally focused on primary impacts, namely those related to residual contamination, such as potential remaining health risks. Various sustainable remediation efforts have made it clear that consideration of secondary impacts that stem from the installation and operation of the treatment technology itself must be considered in any decision-making framework. Some specific secondary environmental and social impacts include:

- Energy Use – High levels of electricity use for operating pump-and-treat and high-temperature systems has become a concern for many remediation installations, both from a cost perspective and an air quality perspective. In many cases, emissions of criteria pollutants from central power plants that provide electricity for remediation projects have had a much larger impact on human and ecosystem health than the local pollution arising from the energy use on-site. Energy consumption for the production of material inputs is also a concern, particularly for the intensive materials such as steel, fossil fuel derived materials such as granular activated carbon, and high-volume materials that require significant transport by heavy trucks, such as clay.

- Water Use – Apart from the contaminated groundwater that is the subject of treatment, systems that use water as a solvent or that require regeneration of spent media can use large quantities of additional water. This can be an added strain on local supplies, particularly in parts of the country that are already experiencing water scarcity issues.

- Worker Exposure / Worker Health and Safety – As with any construction or machinery operation project, there is a risk to workers on remediation sites, both of acute injury and of chronic effects stemming from the work environment.

- Air Emissions and Dust – The construction of large remediation projects can result in a marked increase in local traffic and dust, especially during site preparation.

Most groups discussing sustainable remediation and technology evaluation now recommend incorporating secondary effects such as these, at varying levels of topical coverage, as reviewed in the following section.

2 A Review of Metrics and Indicators for Sustainable Remediation

This project is not the first to consider sustainability criteria in making technology choices around remediation, even within the military. Several groups have made recommendations or created decision support tools around green or sustainable remediation. The bottom line is that there is no standardized method for evaluating remediation technologies on sustainability terms, although there are several useful frameworks in use currently. In the following sections, sustainable remediation efforts at other institutions are reviewed and discussed as they relate to the current National Defense Center for Energy and Environment (NDCEE) work.

2.1 U.S. EPA Office of Solid Waste and Emergency Response (OSWER)

The **U.S. EPA Office of Solid Waste and Emergency Response (OSWER)** has published a set of Best Management Practices (BMPs) for green remediation. These are a mix of specific and more general recommendations, backed up by 25 case studies. The BMPs cover a similar range of sustainability issues as our current NDCEE work. For some issues such as habitat restoration that are difficult to measure, these BMPs are probably more effective than quantitative metrics at guiding green remediation.

> OSWER cleanup programs should consider these recommended elements when carrying out greener cleanup environmental footprint assessments and evaluating best practices that may be useful during the cleanup process.
>
> 1. Minimize Total Energy Use and Maximizes Use of Renewable Energy
>   - Minimize energy consumption (*e.g.*, use energy efficient equipment)
>   - Power cleanup equipment through onsite renewable energy sources
>   - Purchase commercial energy from renewable resources
>
> 2. Minimize Air Pollutants and Greenhouse Gas (GHG) Emissions
>   - Minimize the generation of GHGs
>   - Minimize generation and transport of airborne contaminants and dust
>   - Use heavy equipment efficiently (e.g. diesel emission reduction plan)
>   - Maximize use of machinery equipped with advanced emission controls
>   - Use cleaner fuels to power machinery and auxiliary equipment
>   - Sequester carbon onsite (*e.g.*, soil amendments, revegetate)
>
> 3. Minimize Water Use and Impacts to Water Resources
>   - Minimize water use and depletion of natural water resources
>   - Capture, reclaim and store water for reuse (*e.g.*, recharge aquifer, drinking water irrigation)
>   - Minimize water demand for revegetation (*e.g.*, native species)
>   - Employ best management practices for stormwater
>
> 4. Reduce, Reuse and Recycle Material and Waste
>   - Minimize consumption of virgin materials
>   - Minimize waste generation
>   - Use recycled products and local materials
>   - Beneficially reuse waste materials (*e.g.*, concrete made with coal combustion products replacing a portion of the Portland cement)
>   - Segregate and reuse or recycle materials, products, and infrastructure (*e.g.* soil, construction and demolition debris, buildings)
>
> 5. Protect Land and Ecosystems
>   - Minimize areas requiring activity or use limitations (*e.g.*, destroy or remove contaminant sources)
>   - Minimize unnecessary soil and habitat disturbance or destruction
>   - Minimize noise and lighting disturbance

In addition to these specific BMPs, OSWER has published many documents and case studies about green remediation that provide a discussion and context for more specific and quantitative metrics, including a primer (EPA, 2008) and an excellent web resource: http://www.clu-in.org/greenremediation/ These materials aided in the selection and coverage of metrics for the evaluation tool presented in Section 5, and provided information on strategies for scoring some of the quantitative metrics.

2.2 The Sustainable Remediation Forum (SURF)

The Sustainable Remediation Forum (SURF), a group consisting of remediation professionals, has published an extensive white paper (SURF, 2009) on the topic of sustainable remediation practices, with detailed recommendations on particular environmental issues and metrics to consider.

Initial green remediation efforts focused on fossil fuel and electricity consumption and resultant GHG emissions, with the primary recommendation being to use renewable sources of power. The authors state that this is still the focus of most existing tools, even though sophisticated models exist for examining other aspects of environmental impact.

The SURF white paper recommends applying Life Cycle Assessment (LCA) tools to the evaluations, where possible. The authors make very clear that there is not at present a standard set of metrics at the present time, but several are suggested in the course of the paper:

Some considerations of a sustainable remediation unit could be:

- kg of contaminant removed per pound of GHG;
- kg of contaminant removed per increase in ecological service;
- kg of contaminant removed per increase in human-use value;
- kg of contaminant removed per consumption of natural (e.g., soil disposed) or nonrenewable resource (*e.g.*, fossil fuel); and
- kg of contaminant removed per increase in restored volume of groundwater, surface water, soil, or sediment.

Additional sustainability goals are provided in the document as well, which are attached in the following pages. The SURF study recommends developing a flexible software tool that can be applied to different sites, contaminants, and technologies. This tool should build as much as possible on similar efforts elsewhere within the military and remediation industry, perhaps in consultation with other groups doing similar work, with an eye towards standardization and ease of use.

The need for tool flexibility as expressed by SURF was a major motivation for the open scoring and weighting structure of the tool developed under this project.

2.3 Life Cycle Assessment Metrics

There have been several research articles that apply LCA methods to evaluating the environmental performance of different remediation technologies. LCA is a framework and analytical tool for considering all of the material and energy inputs over the entire life cycle of a treatment installation and examining their impacts for a number of environmental categories, such as GHG emissions or ecosystem toxicity. It is these impact categories that correspond to the types of metrics proposed by OSWER and SURF.

Diamond *et al.* (1999) put forth a life cycle management and framework for considering the scope of sustainable remediation metrics. They propose a time horizon of 25 years, in order to reliably capture post-treatment effects including partial treatment or storage of contaminated waste. Metrics around soil remediation should consider the effects of off-site treatment as well as the impacts of trucking in new soil. The authors also struggle with the choice of a basic unit for the assessment (called the "functional unit" in LCA). They suggest comparing all treatment scenarios against the cost and environmental impacts of replacing all contaminated soil and groundwater (as a worst-case treatment option). Using the proposed life cycle management framework, the authors apply assess six different treatment options against a list of potential stressors, using possible scores of "low", "medium", and "high" – the main table of results has been excerpted on the following page. No social impacts are considered, but the article provides a useful list of broad environmental impacts associated with remediation activities.

Building on this work, Page *et al.* (1999) apply the life cycle framework to a specific lead-contaminated site in Canada. They examine impacts both related to the operation of the treatment technology (global warming potential, solid waste disposal burden, and toxicity potential) and to the site itself (land use and residual human toxicity). Similarly, Volkwein *et al.* (1999) consider a specific remediation site in Germany contaminated with wood preservatives. The authors propose a functional unit that is based on risk. This means that any treatment technology will be evaluated on the activities needed to bring the contaminated site down to a certain threshold level of risk. In the article, three different treatment alternatives are assessed, and the following quantitative metrics are considered:

- fossil resource use
- water use
- land use
- GHG emissions
- acidification (creating acid rain precursors)
- photo-oxidant formation (creating smog precursors)
- toxicity (taking into account exposure pathways)
- odor
- noise

More recently, Bayer and Finkel (2006) used LCA to evaluate two groundwater remediation options (pump-and-treat and funnel-and-gate), again in Germany. They use a functional unit of whether or not the technology can control the contamination zone, as complete aquifer restoration was not possible. For the pump-and-treat system, the environmental impacts of the production and disposal of Granular Activated Carbon (GAC) far outweighed those arising from electricity consumption for pumping. Their results make clear the importance of considering the entire life cycle of a treatment technology, including material inputs.

Finally, Cadotte *et al.* (2007) raise the important remediation metric of time, setting the functional unit of their analysis as the time required to reach the regulated thresholds for clean soil and groundwater. The authors also consider contamination that can affect both soil and groundwater, unlike previous work that considered these different media in isolation. Both of these points were adopted for the present NDCEE project.

2.4 U.S. Military Applications

2.4.1 Air Force Center for Engineering and the Environment (AFCEE)

The Air Force Center for Engineering and the Environment has developed a sustainable remediation tool (named SRT) that is similar to the one envisioned here in practice but is smaller in scope. The tool was developed by GSI Environmental, Inc. and is Excel-based. The evaluation can be performed at either a rough or fine level of detail. Four technologies are built into the model. Users enter in information about the site and the levels of contamination, and the model outputs results for carbon dioxide (CO_2) emissions, total energy use, cost, safety/accident risk, and natural resource service.

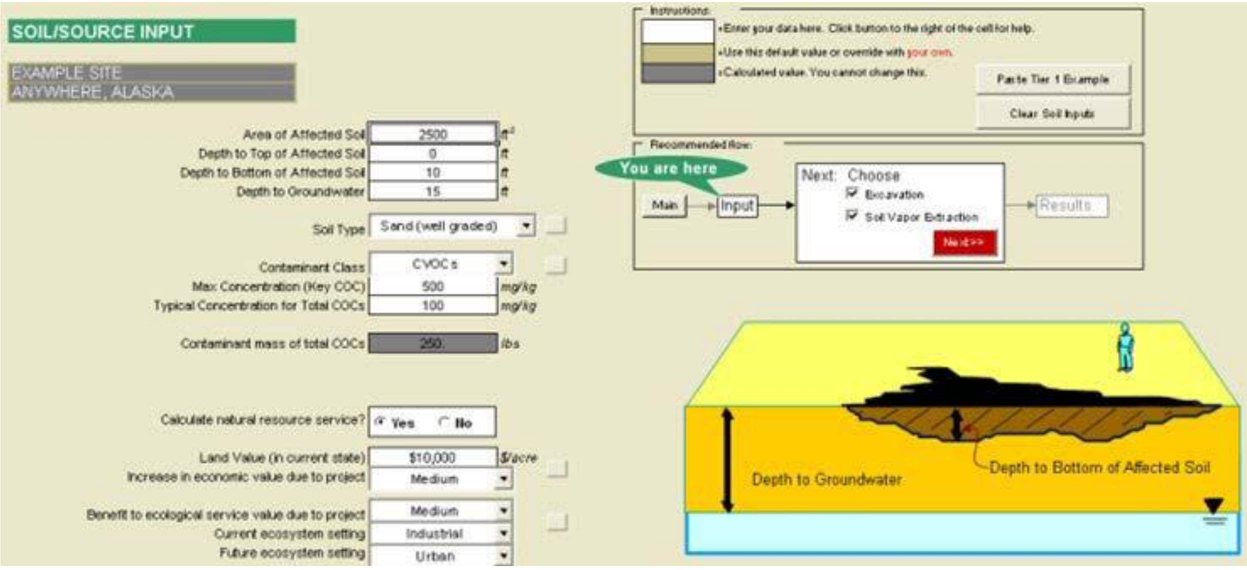


Figure 2.1 Screen shot of the AFCEE SRT

2.4.2 U.S. Army Corps of Engineers (USACE)

The USACE is the primary holder of responsibility for Army remediation projects. Environmental considerations have been incorporated into evaluation of water treatment technologies in the past, for example, in their 'Above-Ground Treatment System Performance Checklist' (USACE, 1999). Aside from treatment efficiency and cost considerations, the checklist also considers releases of process chemicals and possible green chemistry alternatives, and air emissions resulting from treatment operation.

In recent years, according to the SURF white paper (2009):

> The U.S. Army Corps of Engineers is developing a tool to incorporate sustainability into the Department of the Army environmental remedy selection and optimization processes. This tool is structured to explain the process by which sustainability can be incorporated into the U.S. Army's environmental remediation projects. At the core of the tool is a decision flow chart that takes the user from initial project planning to project closeout. The flow chart uses existing Army and federal sustainability practices, to the extent practical, adapting construction/deconstruction and optimization Army policy and procedures as necessary to fully incorporate sustainability. A companion technical memorandum includes instructions on completing each step in the flow chart, with checklists included as appropriate. A draft of the tool has been developed and is currently in agency review; a final guidance document is planned for December 2009.

While it has not been possible to access this tool in order to assess its particulars, it is likely that the level of technical sophistication and detail of required inputs is greater than for the evaluation tool that is

presented in Section 5 in assessing energy and water use, but that it's coverage of sustainability issues is not as comprehensive.

2.4.3 U.S. Army

The U.S. Army already has evaluation criteria for choosing remediation technologies that do not explicitly deal with sustainability, but that nevertheless include relevant items such as fuel and electricity consumption and water pumping requirements, such as the report 'Assessment Criteria to Aid in Selection of Alternative Technologies for Chemical Demilitarization' (National Research Council, 1995).

We recommend that the existing military tools, including that presented here, be shared and perhaps combined in order to save money, time, and effort in development and to ensure consistency. The existing tools are focused again on energy use and resultant emissions and do not cover all of the metrics that are discussed in detail in Section 4 and are incorporated into the evaluation tool (Section 5). This means that significant work will still have to be carried out to extend existing tools to evaluate sustainability in a more comprehensive and holistic manner.

3 Sustainable Remediation and Green Chemistry & Engineering

This section considers metrics and questions presented by past sustainable remediation research and discussion from Section 2 and evaluates their applicability to the 24 Principles of Green Chemistry and Green Engineering, as well as any gaps that exist.

Table 1. How do current sustainable remediation metrics perform against the 12 principles of green chemistry?

Green Chemistry Principle	Current Metrics and Indicators	Gap Analysis
Prevention	Avoided emissions, disruption of land and ecosystems, water runoff, and waste generation; Prevent offsite migration or contamination; Favor technologies that destroy contaminant	Need to address creation of daughter compounds during *in situ* treatment
Atom Economy	Minimize material extraction and use	Can be more specific to treatment reagents or supplies
Less Hazardous Chemical Synthesis	Minimize risk to ecological receptors; Minimize health and safety risk during remedy implementation	Can be more specific to treatment reagents or supplies
Designing Safer Chemicals	Minimize risk to ecological receptors	Can be more specific to treatment reagents or supplies
Safer Solvents and Auxiliaries	None applicable	Need to consider safer alternatives for the solvents or auxiliary chemicals required for the remediation technology (i.e., surfactants in surfactant enhanced aquifer remediation)
Design for Energy Efficiency	Favor low-energy technologies (bioremediation, phytoremediation) where possible and effective; Use passive sampling devices where feasible	Need to assess energy use of the entire project life cycle, including transportation, construction, deconstruction, ancillary facility functions (such as lighting), and embedded energy in materials
Use of Renewable Feedstocks	Use or generate renewable energy to the extent possible; Use native vegetation requiring little or no irrigation	Need to consider renewable feedstocks for chemicals and materials required for the remediation technology (such as biobased surfactants for surfactant enhanced aquifer remediation)
Reduce Derivatives	None applicable	Need to address creation of daughter compounds during *in situ* treatment
Catalysis	None applicable	Need to consider the ability to catalytically break down contaminants rather than stoichiometrically
Design for Degradation	This is a challenge for future engineered materials used by the DoD	Any materials or chemicals remaining in situ after the remediation strategy is complete should be degradable (i.e., surfactants that degrade into safe components after surfactant enhanced aquifer remediation)
Real Time Analysis for Pollution Prevention	Use telemetry or remote data collection when possible; Use operations data to continually optimize and improve the remedy; Integrate flexibility into long-term controls to allow for future efficiency and technology improvements	No gaps identified
Inherently Safer Chemistry for Accident Prevention	Minimize health and safety risk during remedy implementation	Need to evaluate the cost savings associated with the use of less toxic chemicals in terms of storage, transport, and handling

Table 2. How do current sustainable remediation metrics perform against the twelve principles of green engineering?

Green Engineering Principle	Current Metrics and Indicators	Gap Analysis
Inherent Rather than Circumstantial	Favor minimally invasive *in situ* technologies	Use inherently benign material and energy for remediation schemes; Minimize material selection that requires special handling, permitting; Schemes that degrade contaminants into benign forms are preferable to recovery alone
Prevention Instead of Treatment	Avoided emissions, disruption of land and ecosystems, water runoff, and waste generation; Prevent offsite migration or contamination; Favor technologies that destroy contaminant	Need to address creation of daughter compounds during *in situ* treatment
Design for Separation	Maximize materials reuse; Recycle or reuse project waste streams	Choose remediation schemes that do not require further separation steps, such as air stripping post-pump and treat
Maximize Efficiency	Minimize waste	The metric of time should be introduced as a measure of efficacy; Site/land disruption should be considered
Output-Pulled Versus Input-Pushed	None applicable	Chemicals and materials should produced and consumed in sync to avoid inventory storage; Remediation schemes should work with natural systems flows (such as groundwater gradients for pump and treat)
Conserve Complexity	Maximize biodiversity; Minimize soil and habitat disturbance; Prevent cultural resource losses	No gaps identified
Durability Rather than Immortality	None applicable	Remediation system components should not be permanent installations or cause permanent site changes remaining after clean up
Meet Need, Minimize Excess	Minimize waste	The metric of capacity should be introduced as a measure of efficacy
Minimize Material Diversity	None applicable	Remediation schemes should be simple and appropriate to operate and maintain under anticipated field conditions
Integrate Material and Energy Flows	None applicable	Need to consider life cycle metrics that account for the environmental impacts of energy and materials use together over the entirety of the remediation project
Design for Commercial "Afterlife"	None applicable	Need to incorporate environmental impacts associated with treatment decommissioning
Renewable Rather Than Depleting	Use or generate renewable energy to the extent possible	Give preference to biobased treatment materials over synthetic, petroleum-derived materials

4 Updated Sustainable Remediation Metrics for the U.S. Army

Based on proposed sustainable remediation metrics (Section 2) and insights into gaps using the Principles of Green Chemistry and Green Engineering, the purpose of this section is to develop a comprehensive framework for evaluating the environmental preference of various technologies for the treatment and remediation of emerging contaminants on Army sites. This framework will encompass logistical, environmental, and sustainability concerns using the principles of Green Chemistry and Green Engineering and will be appropriate for all substances currently on the Emerging Contaminants (ECs) Directorate Action List, namely

Perchlorate
Royal Demolition Explosive (RDX)
Trichloroethylene (TCE)
Naphthalene
Hexavalent Chromium
Beryllium
Tungsten

The framework will include the following environmental and sustainability considerations, listed below. With each consideration or issue, several indicators or metrics are proposed to measure progress in a readily quantifiable manner.

Treatment efficacy *quantitative metrics for the rate and completeness of reduction or removal of ECs*

- Percent reduction EC after treatment over a fixed period of time (measure concentration after remediation & concentration before remediation)
- Time required for a fixed reduction in EC concentration to the regulatory limit; for example, the time required for the technology to achieve 4 log reduction in perchlorate from 100,000 to 10 micrograms per liter (µg/L)
- Capacity of the treatment technology, compared to estimated size of contaminant plume (ratio)
- Whether or not the treatment technology permanently destroys the contaminant

Nature of residuals *methods of characterization of any treatment byproducts that may also impact human and ecosystem health*

- Total amount of hazardous byproducts (daughter compounds) created during the treatment process (pounds/tons/etc.), unrelated to the EC itself
- Total risk of hazardous byproducts created during the treatment process, apart from the EC itself, to humans and surrounding ecosystems

Inherently benign *evaluation measures of the upstream and downstream impacts of the treatment technology itself*

- Total amount of hazardous and non-hazardous waste generated from treatment (pounds/tons) for each media: air, water, and solid waste.
- Normalized waste generation for each media (pounds/tons per g EC removed)
- Biodegradability or persistence of materials used in the treatment technology
- Total amount of hazardous materials or reagents used as inputs in the treatment itself (weight/volume), or normalized (pounds/liters per g EC removed)
- Inherent toxicity of the materials or reagents used in the treatment technology
- Proportion of materials recycled or reused in the treatment operations (%, excluding water)
- Amount of land required to carry out treatment technology (acres)
- Existence of run-off to nearby surface waters (yes/no)

- Existence of a dust reduction management plan (yes/no)
- Existence of innovative materials or energy cascading (yes/no)
- Proportion of electricity derived from local renewable sources (%)

Worker health & safety *factors for gauging the impacts on military and civilian personnel during the application of the technology*

- Percentage of employees required to be trained in safety and emergency practices relevant to the operation of the technology
- Rates of injury / exposure resulting from the treatment technology, based on statistics from previous projects, normalized by projected hours of operation
- Ranking of worker comfort, based on ergonomic issues, noise, humidity, temperature, based on testimony from previous projects

Social/Cultural factors *ranking of severity of any social impacts to humans both on the training ranges and in the surrounding communities*

- Projected additional impact on local drinking water supplies near the site (projected number of water wells/ persons affected) over the lifetime of the treatment; for example, a treatment with a slow rate may allow for more movement of the plume and further contamination
- Projected increase in traffic during commissioning and decommissioning (# of trucks on local roads)
- Measure of decibel level at a fixed distance from the treatment site
- Air quality standards at the treatment site sulfur oxides, nitric oxides (PM2.5 concentrations)
- Intensity of odor at a fixed distance from the treatment site
- Lighting disturbance to the local community
- Disturbance of local archaeological resources
- Number of required community education programs pertaining to the contaminant and treatment technology, as per U.S. Army/Construction Engineering Research Laboratory (CERL) submissions of risk management plans to the EPA
- Involvement of community members as stakeholders in the planning process
- Land appreciated due to the treatment
- Benefits to the local economy, either through direct employment or indirectly through the purchase of goods and services

Life cycle direct environmental impacts

quantitative assessment of non-health environmental impacts of each treatment technology for on-site activities

- Total or normalized energy used over the lifetime of the treatment (Joules or Joules per g EC removed), including commissioning, operation, maintenance, and disposal of any byproducts
- Total or normalized fossil energy used over the lifetime of the treatment (Joules or Joules per g EC removed), including commissioning operation, maintenance, and disposal of any byproducts
- Total or normalized GHG emissions over the lifetime of the treatment for direct fuel use and electricity consumption (tons CO_2e or tons CO_2e per gram EC removed), including operation, maintenance, and disposal of any byproducts
- Total water usage over the lifetime of the treatment (gallons/Liters), pegged to an indicator of local water availability
- Normalized water usage (gallons/Liters per g EC removed)

Ecosystem considerations

metrics for assessing any potential detrimental impacts to local ecosystems, wildlife, and habitat

- Possibility of using native vegetation for landscaping in concert with the treatment technology
- The existence of wildlife habitat that is affected through the installation and operation of the specific treatment technology

In addition to the social and environmental considerations above, the following factors will also determine preference in evaluating EC treatment technologies:

Cost

- Total life cycle cost over the duration of the treatment, including commissioning, operation, maintenance, and decommissioning

Compliance with internal and external directives and/or legislation

the application of any given treatment technology must be in compliance with existing rules and directives from DoD, EPA, U.S. Congress, and should also consider the concerns of state and local governments

5 Sustainable Remediation Evaluation Tool and Case Study

In order to implement the framework of metrics presented in Section 4, an Excel spreadsheet-based evaluation tool was created with an open, flexible structure and ease of use. The tool was then used to evaluate a specific technology as a case study and method of validation. The technology chosen was a traditional pump-and-treat system for perchlorate, as this type of system has been used at several sites and operational data are relatively easily obtained.

The tool can be used to compare various treatment regimens side-by-side according to their performance on these sustainability metrics. The summary page contains basic information about the site, gives the unweighted and weighted final evaluation scores for each technology side-by-side, and presents a number of normalized sustainability metrics that are of major concern, as shown in Figure 5.1.

GENERAL SITE INFORMATION						
Site Name	Massachusetts Military Reservation					
Site Location (Address)	Cape Cod, MA					
Number of Personnel	400					
Plume Name / ID	Demo 1					
Contaminant Type	perchlorate					
Type of Contamination	groundwater					
Size of contaminant plume	5,000,000,000	liters				
Contamination Concentration	40	µg/L				
Total Amount of Contaminant	200,000	g				
Regulated Concentration Limit	4	µg/L				
SCORING SUMMARY	**Technology 1**	**Technology 2**	**Technology 3**	**Technology 4**		**Weigting**
	Pump and Treat	*Tech2*	*Tech3*	*Tech4*		
Treatment Efficiency	30	48	30	100		20%
Residuals	100	100	100	100		0%
Inherently Benign	55	50	50	60		20%
Worker Health & Safety	55	70	70	70		20%
Social/Cultural Factors	65	72	70	90		10%
Life Cycle Environment	53	92	84	84		25%
Ecosystem Considerations	100	50	100	50		5%
	53	***66***	***63***	***78***		**100%**

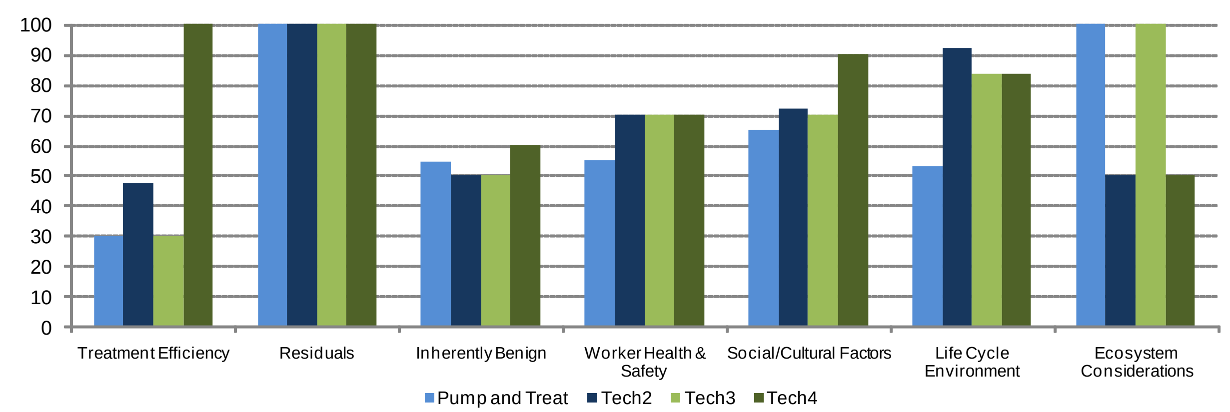


Figure 5.1 Screen shot of the Summary page of the sustainable remediation evaluation tool

A technology summary sheet has also been created for each type of treatment system that is evaluated, for quick reference. An example sheet is shown in Figure 5.2. The top of each technology summary shows a graph of aggregate performance for each sustainability category, along with the weighted final

score. Underneath this are the individual scores for each metric, organized by category. To the left of each metric are graded red boxes that reflect the performance of the treatment technology on a specific metric. The darker the shaded box, the worse the performance. This coloring system allows for users to identify quickly the metrics for which the technology in question performs poorly. In the lower right-hand quadrant of the sheet, various normalized sustainability metrics are given, such as GHG emissions per g of contaminant treated. These metrics correspond most closely with those suggested by SURF and other groups for standard measures of performance.

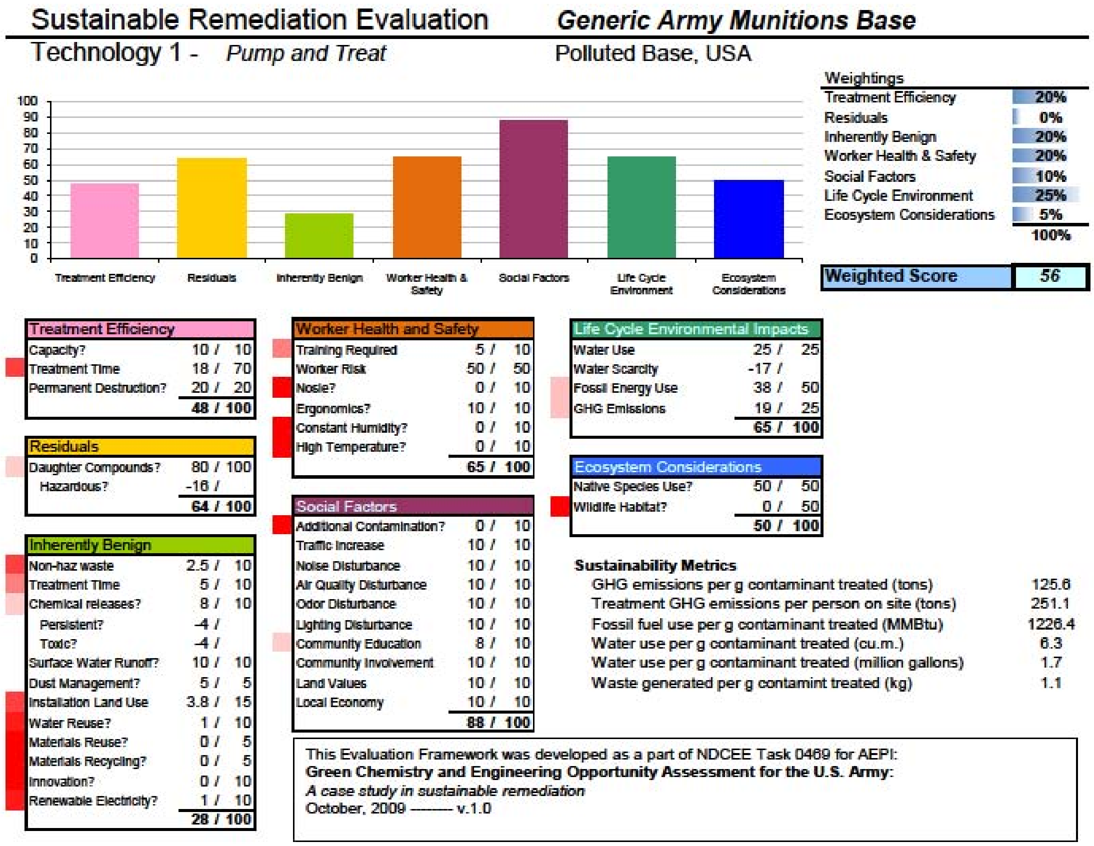


Figure 5.2 Screen shot of the Technology Summary page of the sustainable remediation evaluation tool

5.1 How to Use the Tool

The complete worksheet tool is located in Appendix A and detailed instructions for use are given in the first 'Introduction' tab of the worksheet. Users should proceed sequentially through the worksheet, filling out those fields that appear in yellow.

- **Technology Summary** (**Tech1**, **Tech2**, etc.) – These are filled out automatically and should not be altered except for formatting purposes.
- **Summary** – This sheet is where users should fill out initial information about the site, including name, location, number of personnel, and then several fields about the size and type of contamination. These fields are mandatory, as they are linked throughout the rest of the workbook. This sheet is also where users should determine the categorical weighting factors.
- **Treatment Eff** – Users should fill out responses for each of the *three* metrics, with the units specified in column B. Yes/no fields will have drop-down menus.
- **Residuals** – Users should fill out responses for each of the *two* metrics, with the units specified in column B.
- **Benign** – Users should fill out responses for each of the *thirteen* metrics, with the units specified in column B.
- **WH&S** – Users should fill out responses for each of the *six* metrics, with the units specified in column B.
- **Social** – Users should fill out responses for each of the *ten* metrics, with the units specified in column B. Rank fields will have drop-down menus for "none", "mild", "moderate", and "severe". Any other response will return an ERROR message.
- **Life Cycle** – Users should proceed through this sheet carefully, as there are several automatic fields. Based on *three* water metrics, total and normalized water use will be calculated automatically. Based on *four* fuel and electricity metrics, total fuel and electricity use will be calculated automatically. Users should then specify the region of the country where the treatment site is located. Life cycle fossil fuel use and GHG emissions will then be calculated automatically. These metrics correspond to fuel and emissions from on-site use and purchased electricity *only*, and do not reflect any upstream or embodied energy or materials.
- **Ecosystem** – Users should fill out responses for each of the *two* metrics, with the units specified in column B.

After filling out these fields, the remainder of the sheet will fill in and format automatically. Users can then refer to the **Summary** and **Technology Summary** sheets for the evaluation output. The scoring system and weightings can also be changed by users, as explained in the next section.

5.2 Scoring System

The evaluation tool is based on a hierarchical system of weightings, akin to the Analytical Hierarchy Process within Multi-Criteria Decision Analysis. There are seven categories of metrics, as described in Section 4 above:

1. Treatment Efficiency
2. Residuals
3. Inherently Benign
4. Worker Health and Safety
5. Social/Cultural Factors
6. Life Cycle Direct Environmental Impacts, and
7. Ecosystem Considerations

Each metric receives a weighting within its category, and these weightings sum to a possible score of 100. The 7 total scores for each category are then weighted again, in order to produce a single final score, also out of a possible 100 points. The weightings can be adjusted by users, both at the individual metrics level and at the category level. The tool was designed in this way in order to provide maximum

user flexibility. While the tool comes with a built-in set of reasonable weightings, the assumption is that these will be adjusted by users, as Army professionals are in the best position to determine the relative importance of each category of sustainability metrics for Army remediation projects.

In addition to the weighting system, each metric has a set of logical rules that determine the score given for that metric. For example, a yes/no question gives full points for a “yes” response and zero points for a “no” response. The proportion of waste materials reused on-site given relative points equal to the proportion entered. For several metrics, the points assigned reflect a certain category of performance, such as a “moderate” increase in local traffic or <10,000 cubic meters of water use per gram of contaminant treated. All of the logical rules for scoring the individual metrics are explained in a separate column and can also be changed by adjusting the formulas in the scoring cells, as necessary.

In some cases, metrics have associated questions that affect their final score. For example, in the case of water use, the base score is given for the quantity of water used per gram of contaminant treated. An additional metric asks the user for the local water scarcity conditions. Depending on the response the base score is adjusted down by a certain percentage. Another example is the metric for chemical releases during treatment, which gives a base score depending on if there is a release of chemicals to the environment and adjusts down if the releases are persistent or toxic.

These initial scoring rules were arrived at through reasonable estimation of what constitutes above- or below-average performance.

5.3 Regional Specificity

Some metrics within the evaluation tool rely on regionally-specific information, including fossil energy use, GHG emissions, water scarcity, and ecosystem considerations. The environmental impacts of electricity use vary dramatically depending on the type and quality of fuels used to generate electricity in a given region. Therefore, fossil energy and emissions metrics are calculated automatically by the tool, based on information from the U.S. EPA eGRID database, part of which is embedded in the tool itself. The user must choose a region of the country, which corresponds to one of the 26 electricity subregions defined by eGRID. This choice references specific built-in factors for overall thermal efficiency, fossil fuel proportion in the resource mix, and CO_2 output emissions rate, which are combined with total electricity usage information to give life cycle fossil fuel and GHG emissions results.

For water scarcity and ecosystem considerations, the determination of local conditions is made by users and is not automatic. The tool asks for the level of local water scarcity (“none” to “severe scarcity”) and whether or not a specific technology will impinge on local wildlife habitat or be compatible with native vegetation for landscaping.

5.4 Assumptions and Subjectivity

There are several layers of assumptions that were made in the construction of this technology evaluation tool. It is important to recognize that while the tool is built around quantitative metrics and generates numerical scores for technology comparisons, there is a good deal of subjective judgment that goes into the evaluation.

Most evident are the explicit assumptions made about the relative weightings of metrics within each category, and the weightings of the categories themselves. The scoring scheme for each metric is also user-defined and thus introduces subjectivity. Taken together, the two-tier weighting scheme and the scoring system convert metrics that have absolute quantities that have meaning in reality (gallons of water use, for example) into semi-quantitative scores that only have meaning as a framework for making decisions (such as a final score of 54). In order to ensure that the technology evaluation is not subject to undue subjective bias, it is crucial that weighting schemes be consistent and be arrived at by consensus.

There are also implicit assumptions in the evaluation tool. First, certain metrics have been chosen for inclusion, based on past research and consensus judgment of the NDCEE working group, while others have been excluded. However, the tool was designed for a widely-used platform (Excel) so that metrics can be added or removed easily. Second, the tool focuses on activities that take place on or near the site. A full life cycle assessment treatment of energy would consider not just the electricity and fuel needed to run the treatment system, but also the energy required to manufacture and transport any treatment chemicals or machinery, for example. These indirect impacts can be important but are also numerous and difficult to quantify precisely, and so the system boundary, or scope, for the assessment was taken to be the treatment site and the local communities.

5.5 Case Study: Pump-and-Treat of Perchlorate

In order to demonstrate and validate the evaluation tool, the project working group decided to evaluate a typical pump-and-treat system for perchlorate, based on the prevalence of this emerging contaminant on military ranges and testing grounds, as well as relatively good access to empirical treatment data.

5.5.1 Presentation of the site, contamination, and background

The site chosen for evaluation was the perchlorate plume at Camp Edwards in the Massachusetts Military Reservation (MMR) on Cape Cod, Massachusetts. Perchlorate from live training exercises has created a contaminant plume roughly 9,200’ x 1,400’ x 90’ and maximum contaminant level ranging from 40-140 μg/L. Several pump-and-treat systems were set up in 2004-2005 that initially used GAC for adsorption, but that have since switched over to nitrate selective ion exchange resins. The system in question has a capacity of 220 gallons per minute (gpm).

The contamination has had serious drinking water implications, as MMR is situated over the sole source aquifer for Cape Cod. The Town of Bourne has had to shut down some of its extraction wells and a significant proportion of the town’s residents are being provided with bottled water. Remediation efforts at the site have received intense scrutiny from state and local government and press, and community involvement and education have also been substantial.

There are other remediation activities at the site, which also hosts Otis Air Force Base. The combined electricity requirements for all pump-and-treat systems are considerable, and so a 1.5 megawatt (MW) wind turbine has been installed on-site in order to provide some local renewable energy and reduce demand on combustion-based electricity generation.

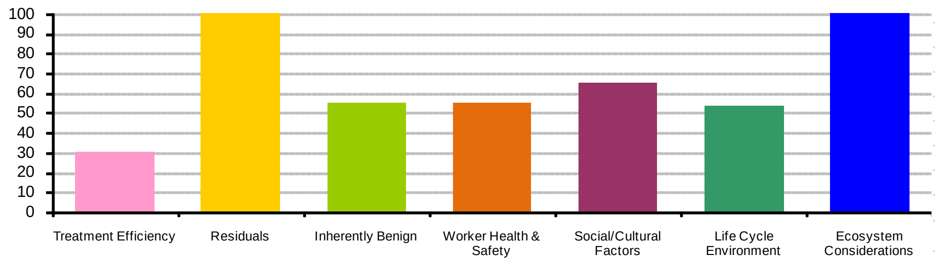
5.5.2 Scoring of the technology using the tool

Information about the site and associated treatment data was collected from a variety of sources, including Sellers *et al*. (2007), the USEPA site for Federal Facilities Restoration and Reuse (2004), the EPA Region 1 site for the MMR (2009), and the Installation Restoration Program for the MMR (2009). Where specific data were not available, such as for non-hazardous and hazardous waste generation, generic data were used from sources including California EPA (2004) and Sellers *et al*. (2007). It was assumed that the system uses a catalytic chemical reduction process to destroy perchlorate in the waste regeneration brine.

All relevant data were entered into the evaluation tool, producing a Technology Summary sheet shown in Figure 5.3. This technology performed poorly overall in the evaluation, mainly due to high energy and water use, the lack of material reuse and recycling possibilities, and a long treatment time. The pump-and-treat system and subsequent brine treatment do not produce any treatment by-products, and so the technology performed well in the Residuals section. The systems were installed on land that had already been disturbed, and so were not considered to impinge further on any wildlife habitat, giving the technology a decent score as well for Ecosystem Considerations. While the single weighted score for the pump-and-treat was 53/100, this number is based on arbitrary category weightings.

Sustainable Remediation Evaluation — *Massachusetts Military Reservation*

Technology 1 - *Pump and Treat* — Cape Cod, MA



Weightings	
Treatment Efficiency	**20%**
Residuals	**0%**
Inherently Benign	**20%**
Worker Health & Safety	**20%**
Social/Cultural Factors	**10%**
Life Cycle Environment	**25%**
Ecosystem Considerations	**5%**
	100%
Weighted Score	***53***

Treatment Efficiency		
Capacity?	10 /	10
Treatment Time	0 /	70
Permanent Destruction?	20 /	20
	30 /	**100**

Residuals		
Daughter Compounds?	100 /	100
Hazardous?	0 /	
	100 /	**100**

Inherently Benign		
Non-haz waste	10 /	10
Treatment Time	2.5 /	10
Chemical releases?	10 /	10
Persistent?	0 /	
Toxic?	0 /	
Surface Water Runoff?	10 /	10
Dust Management?	5 /	5
Installation Land Use	7.5 /	15
Water Reuse?	4.8 /	5
Materials Reuse?	0 /	5
Materials Recycling?	0 /	5
Innovation?	0 /	5
Renewable Electricity?	5 /	20
	55 /	**100**

Worker Health and Safety		
Training Required	0 /	10
Worker Risk	25 /	50
Nosie?	0 /	10
Ergonomics?	10 /	10
Constant Humidity?	10 /	10
High Temperature?	10 /	10
	55 /	**100**

Social/Cultural Factors		
Additional Contamination?	0 /	10
Traffic Increase	8 /	10
Noise Disturbance	10 /	10
Air Quality Disturbance	8 /	10
Odor Disturbance	10 /	10
Lighting Disturbance	10 /	10
Archaeol. Disturbance?	0 /	10
Community Education	4 /	10
Community Involvement	10 /	10
Land Values	0 /	5
Local Economy	5 /	5
	65 /	**100**

Life Cycle Environmental Impacts		
Water Use	19 /	25
Water Scarcity	-3.2 /	
Fossil Energy Use	25 /	50
GHG Emissions	13 /	25
	53 /	**100**

Ecosystem Considerations		
Native Species Use?	50 /	50
Wildlife Habitat?	50 /	50
	100 /	**100**

Sustainability Metrics	
GHG emissions per g contaminant treated (tons)	9.9
Treatment GHG emissions per person on site (tons)	2.5
Fossil fuel use per g contaminant treated (MMBtu)	88.8
Water use per g contaminant treated (liters)	255.5
Water use per g contaminant treated (gallons)	67.5
Waste generated per g contamint treated (kg)	0.4

This Evaluation Framework was developed as a part of NDCEE Task 0469 for the Army Environmental Policy Institute:
Green Chemistry and Engineering Opportunity Assessment for the U.S. Army:
A case study in sustainable remediation
November, 2009 -------- v.1.1

Figure 5.3 Performance evaluation of the perchlorate pump-and-treat system at MMR

6 Recommendations and Next Steps

6.1 Expanding Use and Flexibility of Tool

The main output of this NDCEE project is an appropriate set of sustainable remediation metrics and an evaluation tool that puts these metrics into an easy-to-use framework for technology evaluation. This tool was created expressly with the flexibility to adjust all of the weighting parameters and scoring rules, as well as to add or remove metrics as necessary.

As a near-term next step, a further test of the remediation assessment tool at multiple Army locations would provide more data and feedback on its utility. The locations could be a combination of U.S. and overseas locations, particularly those in Iraq and Afghanistan. The acquisition of additional data would permit an evaluation of how subjectivity in the scoring/weightings affects the ability to generalize about the efficacy of the tool across a larger Army installation sample. An important question to ask in this additional study is a characterization of the end-users and potential feedback from them on the functionality of this tool.

Following this, and in order to further promote its evolution and adoption, potential users should conduct their own pilot evaluation of an actual treatment site using the tool, preferably one that uses *in situ* treatment or some other technology that is unrelated to the pump-and-treat system that was evaluated here. The metrics included in the tool should apply generally to all possible treatment technologies, and performing initial evaluations across a broad range of treatment options may reveal possible areas for improvement.

Following further validation by the Army, it would be useful to conduct an internal workshop in order to decide:

1. Whether and which metrics should be added or removed;
2. If any of the scoring rules needs to be adjusted to reflect the ranges of performance for the technologies that the Army might use; and
3. How the two levels of weightings should be adjusted in order to reflect the relative importance of each metric and category to Army users.

While this tool is intended for Army use, it can both influence and adjust to the ongoing debate around standardizing metrics for sustainable remediation. Consensus-based standards are beginning to take shape, through the work of SURF, the EPA, and others. If, at some future date, there emerges a standard set of sustainability remediation metrics in the U.S. or internationally through, these metrics can easily be incorporated into the tool. Scoring rules can be changed in order to reflected advances in BMPs or technological efficiency.

The main feature of this evaluation tool is the hierarchical weighting system. While such a system necessarily introduces subjective bias into the evaluation, the NDCEE working group believes that such bias will always exist when examining questions of sustainability that cover a broad array of issues that must be considered in parallel. Therefore, a transparent decision-making scheme should be a main feature of any framework for measuring and assessing sustainable remediation.

Finally, we recommend that the tool always be kept in an Excel spreadsheet format, as it will be broadly compatible and easily transferable among potential users, both within and outside of the Army.

6.2 Cooperative Research within the Military

Based on the experience of this NDCEE project, it is becoming increasing clear that an effort needs to be undertaken across the military to identify best sustainability practices in terms of Green Chemistry and Green Engineering to minimize duplication and identify gaps in current activities. It is clear that many

aspects of the broad organization could benefit from a single activity that has been piloted and demonstrated in the context of one branch. It is also clear that this conversation should be inclusive of all of the organizations that support the military's mission including contractors, civilians, local communities, and other relevant stakeholders. Likely, the most appropriate approach would be to identify one or more high priority areas across the broad organization that could be advanced through Green Chemistry and Green Engineering. This would provide a pool of expertise, perspectives, and resources to identify, pilot, and test a joint solution to a common challenge.

In the case of sustainable remediation, the recent memorandum 'Consideration of Green and Sustainable Remediation Practices in the Defense Environmental Restoration Program' requests updates about activities from each DoD Component. While the Army and the Air Force have been most active in the development of a sustainable remediation framework, coordinated effort among all military branches to produce a single evaluation tool will allow the DoD to more effectively shape the national and international debate around appropriate metrics, as well as saving time and effort.

As a next step here, a one day-or-so workshop is recommended that brings together multiple stakeholders that have an interest in incorporating Green Chemistry/Green Engineering into remediation. As reviewed in Section 2, the Air Force Center for the Engineering and the Environment and the U.S. Army Corps of Engineers' U.S. Army Engineer and Support Center (Huntsville) have developed other remediation tools or multiple checklists. The workshop could bring together AFCEE, USACE, and other Department of Defense personnel, and possibly representatives from the Environmental Protection Agency, the Department of Energy, state environmental offices, professional/contractor organizations, and international organizations. The workshop attendees would discuss what a "unified" remediation assessment tool should contain, what revisions might be needed in one or more existing tools to get to a "unified" tool, how to test a "unified" tool in different locations to determine how well the tool functions in the field, what might then be needed to be adjusted, and who the intended user is or should be.

6.3 Systemic Application of Green Chemistry/Green Engineering within the Army

The greatest value to be realized from the application of Green Chemistry and Green Engineering Principles is through a systemic approach. This means integrating Green Chemistry and Green Engineering efforts throughout the organization regardless of existing management or functional boundaries. Furthermore, this means applying Green Chemistry and Green Engineering across the life cycle of the chemical, material, product, process or system to advance the goal of optimizing human health and environmental protection rather than shifting these burdens from one life cycle stage to another.

If the Army is to move towards greater sustainability of its operations, it needs to indentify and assess the multiple interlinked systems that affect operation and maintenance of its bases in particular. Thus, the principles of Green Chemistry and Green Engineering should be integrated into existing processes as much as practicable. One remediation assessment tool to do this is the technology evaluation tool that is presented in the present study. However, complementing this tool should be the use of other proven management efficiency tools, such as Kaizen or Six Sigma to also evaluate the existing processes to determine how they can be made more efficient and effective. The existing processes also need to be evaluated to determine how much energy and water is currently being used and how their use can be decreased. The Army Environmental Policy Institute is currently investigating the current and 30-year-projected water availability at ten U.S installations and three overseas installations. Any Green Chemistry/ Green Engineering/ Six Sigma process improvement study would also need to incorporate what the future projected water availability will be to determine the continued viability of any "greened/leaned" processes.

To demonstrate the potential power and effectiveness of Green Chemistry and Green Engineering for the Army or the military complex, writ large, a rigorous effort should be undertaken to answer the following questions:

- Can Green Chemistry advance the mission of the Army? How?
- How does Green Chemistry support the Army's strategic plan for sustainability?
- How can Green Chemistry enhance the abilities and skills of the war fighter?
- How can Green Chemistry make the Army more resilient?
- How can Green Chemistry make the Army more efficient?
- Where are the Green Chemistry opportunities throughout the Army enterprise?
- What are the Green Chemistry imperatives for the Army?
- What are the examples of successful implementation of Green Chemistry in the Army?
- What are the barriers to systematic implementation?
- What mechanisms can the Army exploit to advance Green Chemistry?
- How can the Army support Green Chemistry advances in academia and business?
- How can the Army support Green Chemistry through pilot testing and feedback of Green Chemistry Science and Technology (S&T)?
- What are the benefits of Green Chemistry implementation to the Army - today and tomorrow?

To highlight specific potential Green Chemistry and Green Engineering applications that will benefit the mission as well as the environmental and human health, the following examples are provided as possible research questions that could be pursued to advance this agenda.

- Can Green Chemistry develop batteries that are made from benign materials, store orders of magnitude more energy, and are lightweight and compact?
- Can Green Chemistry design flexible fuels that can be used in any Army vehicle?
- Can Green Chemistry make new polymers and materials that are self-healing to be used in everything from fabrics to trucks?
- Can Green Engineering purify water with naturally occurring, locally accessible materials?
- Can Green Engineering design computers, buildings, and bridges for disassembly such that the components can be used in other places and for other purposes?
- What does an Army that produces no waste – uses all of the material and energy that is today thought of as waste as feedstocks for energy or other purposes – what does that Army look like?
- How do we make the uniform of the 21st Century soldier not only self-cleaning and hygienic without water or detergents as well as self-healing if damaged, how do we make it cool the soldier when it’s hot and warm the soldier when it’s cool and produce its own energy?

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APPENDIX A

Technology Assessment Methodology

NDCEE 0469 metrics
scoring v4 (2).xlsx